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Lodgepole Pine Response to Aspen Removal in Variable Radii in the SBSdw2 Variant near Williams Lake, B.C.

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ABSTRACT

A study was established in 1994 in the SBSdw2 variant of the Cariboo-Chilcotin region of the Southern Interior Forest Region to investigate the effects of removing aspen in 50 or 100 cm radii around crop lodgepole pine versus broadcast removal or no treatment. The primary objective of the study was to assess whether the free-growing criterion (current in 1994), which specified that no overtopping vegetation could be present within a 1 m radius around crop trees, was appropriate in pine–aspen stands, or whether a 50 cm radius zone would be adequate.

After 9 years, during which treatments were maintained annually, there were no differences in pine survival or growth between the 50 and 100 cm radius treatments. Even in the untreated control, there was no mortality as a result of vegetation competition, and neither were there vigour losses. There also were no significant differences in pine stem diameter or height as a result of any of the treatments, but height:diameter ratio (HDR) was significantly lower in the broadcast treatment than in the control and 50 cm treatment.

During the 9 years of the study, total aspen density decreased from approximately 50 000 to 22 000 stems ha^{-1}. Tall aspen density (i.e., the density of aspen as tall or taller than the target lodgepole pine) was approximately 5000 stems ha^{-1} at age 9 years. At that time, tall aspen density was more strongly correlated than was aspen basal area with pine stem diameter growth. Related work (Newsome et al. 2003) showing that competition effects are only weakly expressed in 9-year-old pine–aspen stands suggests the need for longer-term measurements at the Tyee Lake site.

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Mixed forests of lodgepole pine (*Pinus contorta* var. *latifolia* Engelm.) and trembling aspen (*Populus tremuloides* Michx.) are common throughout interior British Columbia, particularly in north and central areas of the province. In the Cariboo-Chilcotin area of the Southern Interior Forest Region, aspen commonly regenerates along with planted and natural lodgepole pine in the Sub-Boreal Spruce (SBS), Interior Douglas-fir (IDF), Sub-Boreal Pine–Spruce (SBPS), and Interior Cedar–Hemlock (ICH) zones (Meidinger and Pojar 1991). Historically, aspen has been regarded as a "weed" that competes with conifers, but silviculturists now recognize that there are many benefits to maintaining a broadleaf component within stands.

At low densities, aspen offers advantages to both individual conifers and the site as a whole. Young aspen takes up large amounts of nutrients, particularly calcium, and retains them within the ecosystem (Pastor 1990). Aspen also is more resistant to *Armillaria* and *Phellinus* than most conifers, and its presence slows the spread of these diseases through conifer stands (Morrison et al. 1991; Peterson and Peterson 1995; Gerlach et al. 1997). Young seedlings may experience less frost damage under mature aspen canopies than in clearcuts (DeLong 2000) because of reductions in nighttime radiative heat loss (Stathers 1989); however, this is a more important consideration for white spruce than for lodgepole pine because of differences in frost tolerance (Farnden 1994). Finally, because of its communal root system, sucker-origin aspen is mechanically stable (Strong and La Roi 1983), which may reduce windthrow among neighbouring conifers (Frivold 1985; Yang 1989).

Nonetheless, aspen can compete strongly with young conifers, and at high densities it can reduce both light and soil water to levels that are limiting to conifer growth for at least part of the growing season (DeLong and Tanner 1996). Mechanical "whipping" damage to conifer leaders is also common in aspen stands (Lees 1966). Light availability is of particular importance in pine–aspen stands because both species are very shade-intolerant (Klinka and Scagel 1984a, 1984b); studies have shown lodgepole pine stem diameter growth decreases, height:diameter ratio increases, and crown width decreases where light is limited (e.g., Simard et al. 2001). In low light environments, lodgepole pine is known to allocate more growth to terminal than lateral shoots and to reduce branch number (Chen et al. 1996).

In order to develop strategies by which aspen can be retained in stands where softwood production is the primary objective, silviculturists require information about levels of broadleaves that can be retained without seriously affecting conifer performance. They also require practical ways of using this information to develop cost-effective treatment prescriptions. To address these information needs for the Cariboo-Chilcotin, a retrospective study was conducted in naturally regenerated pine–aspen stands during a 7-year period from 1992 to 1999 (Newsome et al. 2003). Early results suggested that competition from aspen was taking place within a 1.78 m radius of the crop pine, and that competition thresholds were below 5000 aspen stems ha^{-1}. Eventual results revealed that 1000 and 2000 "tall aspen" stems ha^{-1} were appropriate thresholds for 15- to 19-year-old stands in the SBSdw and IDFdk subzones, respectively, but that thresholds tended to decrease with stand age. In response to the earliest retrospective study results, experiments were established in various ecosystems to test the effectiveness of manipulating the density and spatial arrangement of aspen in relation to pine.

This report summarizes the results of an experiment conducted in the SBSdw2 variant to compare the effects of removing aspen in 50 or 100 cm radii around crop pine seedlings with broadcast removal (i.e., removal of all aspen) and an untreated control. The main objective of this study was to evaluate the spatial criterion used in free-growing guidelines that were applicable in 1994. At that time, free-growing guidelines stated that crop conifers in the IDFdk and SBSdw subzones had to be 125% and 150%, respectively, taller than surrounding vegetation within a 1 m radius (B.C. Ministry of Forests 1995). These guidelines have now changed to allow tall broadleaves to be present in one quadrant, but the 1 m radius cylinder around crop conifers continues to play a role in the guidelines (B.C. Ministry of Forests 2002). The work described in this report tests the effectiveness of the 1 m radius free-growing criterion for ensuring that the health and vigour of crop lodgepole pine is not compromised by aspen competition.

A second objective of the study was to test the competitive effect of aspen on crop pine performance in order to confirm findings of the pine–aspen retrospective study (Newsome et al. 2003). Competitive effects were examined in terms of distance between the crop pine and the aspen stems growing within a 1.78 m radius, and in terms of the size of aspen relative to the crop pine. When this experiment was established in 1994, operational brushing prescriptions typically prescribed the removal of aspen within a 2 m radius of crop pine, which tended to result in a more or less broadcast treatment. If smaller treatment radii proved to be as effective as the broadcast treatment for releasing pine from aspen competition, treatment costs could be reduced and the level of aspen retention increased.

2 OBJECTIVES

The study objectives were:

1. to compare survival, growth, and vigour of lodgepole pine in an unbrushed control with three levels of aspen removal: (1) removal of aspen within a 50 cm radius of pine, (2) removal of aspen within a 100 cm radius of pine, (3) removal of all aspen.
2. to use the above results to evaluate the appropriateness of the 1 m spatial criterion used in free-growing guidelines.
3. to compare growth and density of aspen among the control and the 50 cm and 100 cm treatments.
4. to provide a demonstration of variable radius brushing in a pine–aspen complex in the SBSdw2.

3 METHODS

3.1 Study Areas and Site Selection

The Tyee Lake site was chosen because it was characteristic of the Cariboo moist transition and had a dense stand of approximately 15-year-old aspen. In addition, aspen were expected to sucker abundantly following clearing of the site, which was a requirement for the study. The Tyee Lake site is located in the SBSdw2 variant (Sub-Boreal Spruce Dry Warm subzone, Blackwater

Variant), but is transitional to the SBSdw1 (Sub-Boreal Spruce Dry Warm subzone, Horsefly Variant); it is therefore representative of the SBSdw subzone for the Southern Interior Forest Region. The site is at an elevation of 885 m and is flat (0–5% slope). It has a mesic moisture regime and a medium nutrient regime, and is zonal (site series 01) in the SBSdw2 variant. The SBSdw2 variant has mean annual precipitation of 487 mm, a mean annual temperature of 3.4°C, an average of 170 frost-free days per year, and brunisolic zonal soils (Steen and Coupé 1997). The site (mapsheet/opening 93B040-36) was clearcut logged in 1980, after which it regenerated heavily to aspen. In 1993, all aspen were cut with chainsaws and the site was mechanically prepared with a ripper in preparation for this study. The area was fenced to exclude cattle, and lodgepole pine were planted in 1994. The location of the Tyee Lake site is shown in Figure 1.

3.2 Sampling Design and Treatments

This study used a randomized complete block design (RCBD), with three blocks and each of the following four treatments applied to one plot per block:

1. Control (no vegetation removal).
2. All vegetation taller than 10 cm removed within a 50 cm radius of crop pine.
3. All vegetation taller than 10 cm removed within a 100 cm radius of crop pine.
4. All vegetation taller than 10 cm removed within the entire treatment plot (broadcast treatment).

Blocking was based on geographic differences: two blocks were located on one cutblock and the third block at another cutblock a few hundred metres away (Figure 2). Each of the 12 treatment plots (three blocks × four treatment plots/block) was 25 × 25 m in area (0.0625 ha), and contained eight ripper tooth rows that were 2.3 m apart. Plots were spatially separated by at least one ripper tooth row. Lodgepole pine seedlings (PSB 313 1 + 0) were planted at 4-m intervals in the ripper tooth rows, and spacing was staggered in alter-

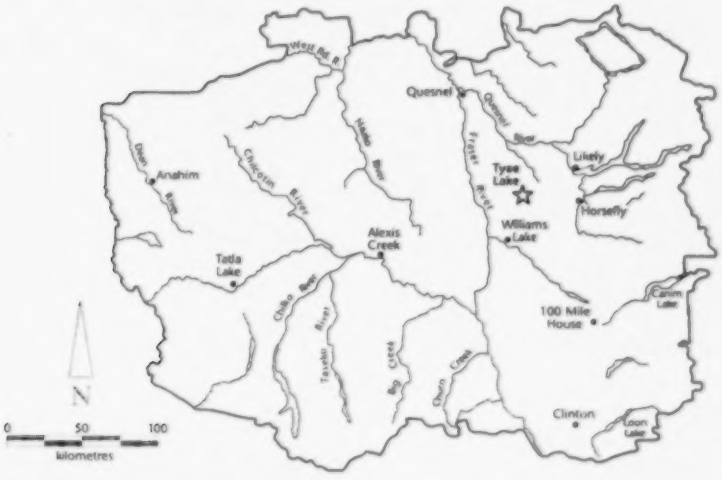

FIGURE 1 *Location of the Tyee Lake study site.*

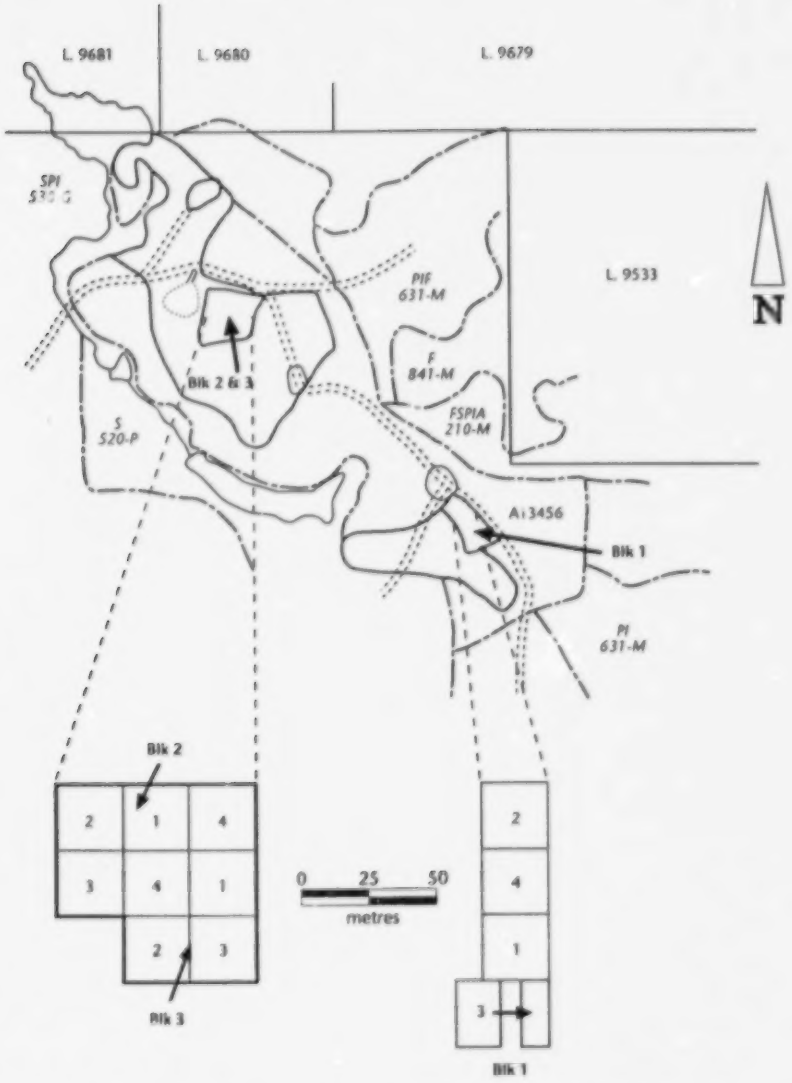

FIGURE 2 *Plot location at Tyee Lake. Treatments are indicated by the following numbers: 1 = control, 2 = 50 cm radius removal, 3 = 100 cm radius removal, and 4 = broadcast removal.*

nate rows to avoid plot overlap. Forty pine seedlings were planted in each treatment plot. Treatments were randomly assigned to plots within blocks. Brushing treatments were maintained annually from 1994 to 2002 by manually removing new aspen suckers with clippers. In the 50 and 100 cm radii treatments, branches were also clipped annually from surrounding aspen to maintain vegetation-free cylinders around the crop pine.

3.3 Measurements

Measurements were carried out in 1994, 1995, 1996, 1998, 1999 (crop pine only), 2000, and 2002.

3.3.1 Crop lodgepole pine The following measurements were carried out for crop lodgepole pine in all assessment years:

- total height
- leader length
- ground-level stem diameter
- survival and vigour
- type and cause of damage
- degree of overtopping

Height:diameter ratio (HDR) was calculated based on ground-level diameter, and increment in height and stem diameter were calculated for specific time periods. Pine survival, vigour, damage, damage cause, and degree of overtopping were assessed according to standard Cariboo Forest Region protocol (Appendix 1).

3.3.2 Neighbouring aspen and willow Neighbouring aspen were assessed within a 1.78 m radius subplot around each of the 40 crop lodgepole pine seedlings in each treatment plot. Willow was sufficiently abundant at the Tyee Lake site that it was initially considered to be a possible contributor to the light competition experienced by small pine seedlings. For this reason, willow was measured along with broadleaves from 1994 to 2000. This procedure was discontinued in 2002 because analyses (unpublished) had shown that the willow was not contributing significantly to competition. The very infrequent black cottonwood (*Populus trichocarpa* Torr. & Gray) and paper birch (*Betula papyrifera* Marsh.) stems that occurred on the site at the start of the study were considered to be willow for measurement purposes, but these species were no longer present by 2002.

The following measurements were carried out for neighbouring aspen and willow from 1994 to 2000 within a 1.78 m radius of crop pine:

- Height
- Stem diameter at ground level. From 1994 to 2000, three representative stems that included the range of sizes for each species (aspen and willow) were selected for measurement. In 2002, the diameters of all aspen stems within a 1.78 m radius of crop pine were measured.
- Stem-to-stem distance (distance from the outside edge of the neighbouring aspen or willow stem to the stem centre of the crop pine).

In 2002, crown-to-stem distance (the distance from the edge of the aspen crown to the stem centre of the crop pine) was also measured for all aspen within each 1.78 m radius subplot. If the crown of a neighbouring aspen tree

overtopped the crop pine (i.e., if the crown had grown directly over the leader of the crop pine), the overtopping distance was measured back to the crop pine stem centre and recorded as negative.

Overall broadleaf density, based on the entire area bounded by each 1.78 m radius subplot (i.e., the number of stems per 10 m^2 plot) was determined from the data. In order to assess the effects of increased light at the edges of the treated areas on aspen self-thinning, and to characterize the stand around the treated area, density based only on the "untreated" portion of each 10 m^2 plot was also calculated (broadleaves had been removed from the "treated" area). For example, in the 50 cm radius treatment, the treated area in each 10 m^2 subplot was 0.785 m^2 and the untreated area was 9.215 m^2, so density in the untreated part was calculated by dividing the number of stems by 9.215 m^2 and converting to stems per hectare. In the 100 cm radius treatment, the treated area was 3.142 m^2 and the untreated area was 6.858 m^2. Both aspen density within the 10 m^2 subplot area (including both treated and untreated areas) and aspen density per hectare in untreated portions of the subplot were considered important characterizations of the stand. Aspen basal area (BA) per subplot (m^2 ha^{-1}) was calculated for 2002, which was the first year that diameter of all aspen stems was measured.

3.3.3 Additional vegetation measurements The following measurements were carried out within the 1.78 m radius subplots in each assessment year to determine whether vegetation other than trees was contributing to competition:

- percent cover and modal height of the shrub layer
- percent cover and modal height of the herb layer

3.4 Analysis

SAS statistical software (SAS Institute Inc. 1996, 1999) was used for all data analyses. Before analysis, data were checked for outliers and normality using PROC UNIVARIATE. Summary statistics were compiled using PROC TABULATE, correlation analysis was done with PROC CORR, and regression models were fitted with the SAS macro NLINMIX (Wolfinger 2000). Analysis of variance was done with PROC GLM (for balanced data only) and PROC MIXED.

3.4.1 Analysis of variance (ANOVA) A mixed-model ANOVA was used to assess the effects of the brushing treatments on lodgepole pine seedling growth parameters (Table 1), broadleaf height, diameter, and basal area (Table 2), and changes in broadleaf density over time (Table 3). ANOVA sources of variation and degrees of freedom differed for pine and aspen because there were no broadleaves present in the complete vegetation removal treatment, and, consequently, there was one fewer treatment in the analyses of broadleaf height and density. The statistical significance of differences between all pairs of treatment means was assessed by the Bonferroni method of multiple comparisons.

3.4.2 Correlation and regression analysis Relationships between lodgepole pine growth and broadleaf density within 1.78 m of the crop pine were investigated by calculating Spearman's rank correlation coefficients for pairings of selected aspen density variables with the following pine variables: (1) height, (2) leader length, (3) stem diameter, (4) height increases during specific periods, and (5) diameter increases during specific periods. Density variables

TABLE 1 *ANOVA table for examining the effects of no treatment, 50 and 100 cm radius removal of aspen, and broadcast removal of aspen on lodgepole pine growth*

Source of variation	Degrees of freedom[a,b]	Type of effect
Block (B)	3 – 1 = 2	Random
Treatment (T)	4 – 1 = 3	Fixed
B × T (treatment plot)	2 × 3 = 6	Random
Error (tree)	n – 12	Random

a Model parameters were estimated by the residual (restricted) maximum likelihood (REML) method with denominator degrees of freedom for testing fixed effects calculated by Satterthwaite's approximation for unbalanced designs (because the number of live pine trees varied among treatment plots).
b *n* is the total number of live pine.

TABLE 2 *ANOVA table for examining the effects of no treatment and 50 and 100 cm radius removal of aspen on broadleaf height, diameter, and basal area*

Source of variation	Degrees of freedom[a,b]	Type of effect
Block (B)	3 – 1 = 2	Random
Treatment (T)	3 – 1 = 2	Fixed
B × T	2 x 2 = 4	Random
Subplot	(40 – 1) × 3 × 3 = 351	Random
Error (tree)	n – 360	Random

a Model parameters were estimated by the residual (restricted) maximum likelihood (REML) method with denominator degrees of freedom for testing fixed effects calculated by Satterthwaite's approximation for unbalanced designs (because the number of trees varied among subplots).
b *n* is the total number of broadleaf stems measured in subplots containing a live central pine.

TABLE 3 *ANOVA table for examining the effects of no treatment and 50 and 100 cm radius removal of aspen on broadleaf density in the SBSdw2*

Source of variation	Degrees of freedom[a,b]	Type of effect
Block (B)	3 – 1 = 2	Random
Treatment (T)	3 – 1 = 2	Fixed
B × T	2 × 2 = 4	Random
Error (subplot)	n – 9	Random

a Model parameters were estimated by the residual (restricted) maximum likelihood (REML) method with denominator degrees of freedom for testing fixed effects calculated by Satterthwaite's approximation for unbalanced designs (because the number of subplots with a live central pine varied among subplots).
b *n* is the total number of subplots with a live central pine.

included: (1) tall aspen (aspen as tall or taller than the crop pine seedling), (2) all aspen, and (3) all aspen plus willow. The infrequent paper birch and cottonwood that had regenerated on the study site were considered to be willow for purposes of analysis.

Tall aspen density was consistently the variable that was most highly correlated with pine size, so that particular relationship was further investigated using regression analysis. A non-linear model of the following form was fitted for all pine growth variables except HDR:

$$y = ae^{bx} + \gamma_{block} + \delta_{treatment\ plot\ (block)} + \varepsilon \quad (1)$$

where y is one of the pine growth variables, x is the density of all broadleaf and conifer trees as tall or taller than the crop pine, and γ_{block}, $\delta_{treatment\ plot\ (block)}$ and ε are, respectively, random errors associated with blocks, treatment plots within blocks, and the residual (tree) error.

A quadratic model was fitted to describe the relationship between HDR and tall aspen density:

$$y = a + bx + cx^2 + \gamma_{block} + \delta_{treatment\ plot\ (block)} + \varepsilon \quad (2)$$

where y is one of the pine growth variables, x is tall aspen density, and γ_{block}, $\delta_{treatment\ plot\ (block)}$ and ε are as defined above for Equation 1.

Using data collected in 2002, Equation 1 was also used to investigate the relationships between tall aspen basal area and pine size.

4 RESULTS

4.1 Lodgepole Pine Performance

4.1.1 Pine survival and vigour Survival and vigour of newly planted lodgepole pine were reduced in the first growing season by voles. The heaviest damage occurred in the control and 50 cm radius treatments, possibly because the greater abundance of vegetation in those treatments provided the best cover for small mammals. Seedlings were sprayed with Anipel® in 1995, after which the damage stopped; however, survival did not stabilize until about 1998. In 2002, when pine seedlings were 8 years old, survival was 74% in the control, 72% in the 50 cm radius brushing treatment, 86% in the 100 cm radius brushing treatment, and 87% in the broadcast brushing treatment (Table 4). Although vegetation competition may have been a contributing factor in some cases, it was never the sole cause of mortality.

Vigour of the surviving lodgepole pine seedlings declined as a result of the vole attack, and then stabilized again as heavily damaged seedlings died and those that were less damaged recovered (Table 4). Most surviving seedlings were in good or fair condition by 2000. Most pine continued to be of at least fair vigour in 2002, but there was an obvious trend of declining vigour with increasing aspen density (Figure 3). Several potential problems with pine health and vigour were observed in 2002. For example, more than 20% of stems in the control and 50 cm treatment were affected by western gall rust (*Endocronartium harknessii* [J.P. Moore] Y. Hirat), as were 16–17% of stems in the 100 cm and broadcast treatments. Sixteen to 25% of pine also had forked stems, missing leaders, or new leaders as a result of an unidentified damaging agent, or possibly because of an unknown stock-related problem. This type of damage occurred in all treatments, including the control, with no trends according to the level of aspen removal.

TABLE 4 *Mean lodgepole pine seedling survival[a] and vigour in 50 cm radius, 100 cm radius, and broadcast brushing treatments, and the untreated control, 1994–2002*

		Control	50 cm	100 cm	Broadcast
Survival (%)					
	1994	100	100	100	100
	1995	94	77	94	95
	1996	94	77	93	96
	1998	79	77	88	96
	1999	79	76	88	93
	2000	78	74	88	92
	2002	74	72	86	87
Good vigour (%)					
	1994	90	82	78	82
	1995	71	51	57	75
	1996	62	46	51	62
	1998	55	55	58	68
	1999	67	64	63	80
	2000	69	64	70	81
	2002	47	51	57	61
Fair vigour (%)					
	1994	9	16	21	18
	1995	15	18	20	14
	1996	21	22	24	28
	1998	23	20	26	28
	1999	11	9	22	11
	2000	8	6	16	11
	2002	25	18	25	25
Poor vigour (%)					
	1994	1	2	1	0
	1995	8	8	17	6
	1996	11	9	18	6
	1998	1	2	4	0
	1999	1	3	3	2
	2000	1	4	2	0
	2002	2	3	4	1

a Moribund and missing seedlings are classified as "dead."

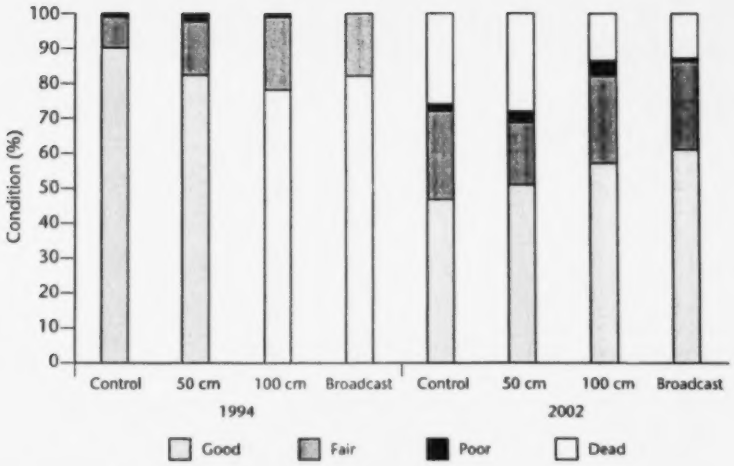

FIGURE 3 *Comparison of lodgepole pine survival and vigour in 50 cm radius, 100 cm radius, and broadcast brushing treatments, and in the untreated control, for the years 1994 and 2002. Moribund and missing seedlings are considered "dead."*

4.1.2 Pine growth Average ground-level lodgepole pine stem diameter increased from 0.4 cm at the time of planting (1994) to 5.0 cm in 2002, with no significant differences between treatments in any of the measurement years ($p > 0.05$). However, a trend of increasing diameter in the broadcast treatment relative to the 50 and 100 cm radius treatments and the control appeared to be developing (Table 5). There also were no significant differences between treatments in diameter or height growth increments for the periods of 1994–1998, 1994–2000, or 1994–2002 ($p > 0.05$, Table 6). Average pine height increased from 28 cm in 1994 to 283 cm in 2002, but there were no significant differences between treatments in any of the measurement years ($p > 0.05$).

Height:diameter ratio (HDR) based on ground-level diameter averaged 68 in the year of planting, and did not differ significantly among treatments ($p = 0.8555$). By 1998, HDR was significantly lower in the broadcast treatment (56) than in either the control (65) or the 50 cm radius treatment (64) ($p = 0.0088$). This trend continued through 2002 when HDR was 51 in the broadcast treatment versus 63 and 62 in the control and 50 cm radius treatments, respectively.

4.2 Neighbourhood Vegetation

4.2.1 Aspen size and density In preparation for establishment of this study, the Tyee Lake site was cleared of aspen and mechanically prepared with a ripper tooth. Following these activities, aspen regenerated vigorously as was expected, but willow regeneration was also abundant enough that it was thought to possibly be contributing to competition. Three data sets were therefore considered: (1) tall aspen, (2) all aspen, and (3) all aspen plus willow. The few paper birch and cottonwood stems on the site were considered to be willow for purposes of analysis.

Except for a short-lived reduction in tall aspen diameter in the 50 and 100 cm radius treatments relative to the control in 1995 (there were no aspen in the broadcast treatment), there were no significant differences in broadleaf

TABLE 5 *Mean[a] lodgepole pine growth in 50 cm radius, 100 cm radius, and broadcast brushing treatments, and in the untreated control, 1994–2002*

		Brushing treatment[b]				
		Control	50 cm	100 cm	Broadcast	p-value[c]
Stem diameter (cm)						
	1994	0.4 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.7410
	1995	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.7 ± 0.1	0.6907
	1996	1.1 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	1.1 ± 0.1	0.3086
	1998	1.9 ± 0.2	1.9 ± 0.2	1.9 ± 0.2	2.2 ± 0.2	0.3799
	1999	2.7 ± 0.2	2.6 ± 0.2	2.6 ± 0.2	3.0 ± 0.2	0.2313
	2000	3.2 ± 0.2	3.3 ± 0.2	3.2 ± 0.2	3.8 ± 0.2	0.1292
	2002	4.7 ± 0.3	4.9 ± 0.3	4.6 ± 0.3	5.6 ± 0.3	0.1237
Height (cm)						
	1994	27 ± 1	28 ± 1	28 ± 1	27 ± 1	0.7008
	1995	35 ± 3	34 ± 3	32 ± 3	35 ± 3	0.6555
	1996	57 ± 4	54 ± 4	50 ± 4	57 ± 4	0.4241
	1998	127 ± 3	121 ± 4	114 ± 4	123 ± 3	0.4575
	1999	157 ± 4	151 ± 5	141 ± 5	155 ± 4	0.4107
	2000	204 ± 5	197 ± 6	183 ± 6	200 ± 4	0.2447
	2002	289 ± 16	296 ± 16	265 ± 16	283 ± 15	0.2614
Leader length (cm)						
	1995	12 ± 1	11 ± 1	10 ± 1	12 ± 1	0.4308
	1996	24 ± 1 a	22 ± 2 ab	20 ± 1 b	24 ± 1 a	**0.0051**
	1997	28 ± 2	27 ± 2	25 ± 2	27 ± 2	0.5497
	1998	41 ± 2	40 ± 2	38 ± 2	38 ± 2	0.4580
	1999	37 ± 2	39 ± 2	36 ± 2	38 ± 2	0.4607
	2000	46 ± 3	47 ± 3	42 ± 2	46 ± 2	0.2563
	2002	46 ± 3	54 ± 3	49 ± 3	47 ± 3	0.1878
Height:diameter ratio						
	1994	67 ± 2	69 ± 2	68 ± 2	67 ± 2	0.8555
	1995	49 ± 2	48 ± 2	46 ± 2	48 ± 2	0.7262
	1996	53 ± 2	52 ± 2	50 ± 2	50 ± 2	0.6020
	1998	65 ± 2 a	64 ± 2 a	59 ± 1 ab	56 ± 1 b	**0.0088**
	1999	61 ± 1 a	61 ± 1 a	56 ± 1 b	53 ± 1 b	**0.0051**
	2000	63 ± 2 a	61 ± 2 a	57 ± 2 ab	53 ± 2 b	**0.0073**
	2002	63 ± 2 a	62 ± 2 a	58 ± 2 ab	51 ± 2 b	**0.0078**

a Values are presented in the form of "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b The site was cleared of aspen prior to the start of the study, and aspen removal in the 50 and 100 cm radius and broadcast treatments was maintained annually.

c Values are in **bold** if they are significant at $p \leq 0.05$, according to analysis of variance. Means are assigned different letters if they are significantly different within the given year according to the Bonferroni test.

TABLE 6 *Mean[a] lodgepole pine height and diameter increments in 50 cm radius, 100 cm radius, and broadcast brushing treatments, and in the untreated control, for specific time periods from 1994 to 2002*

		Brushing treatment[b]				
		Control	50 cm	100 cm	Broadcast	p-value
Diameter increments (cm)						
	1994–1998	1.58 ± 0.05	1.57 ± 0.06	1.58 ± 0.06	1.83 ± 0.05	0.4253
	1994–2000	2.87 ± 0.08	2.94 ± 0.10	2.88 ± 0.10	3.43 ± 0.08	0.1469
	1994–2002	4.3 ± 0.3	4.6 ± 0.3	4.3 ± 0.3	5.2 ± 0.3	0.1374
Height increments (cm)						
	1994–1998	112 ± 3	105 ± 4	100 ± 4	108 ± 3	0.4740
	1994–2000	189 ± 5	182 ± 6	170 ± 6	185 ± 4	0.2682
	1994–2002	274 ± 15	280 ± 15	251 ± 15	268 ± 15	0.2859

a Values are presented in the form of "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b The site was cleared of aspen prior to the start of the study, and aspen removal in the 50 and 100 cm radius and broadcast treatments was maintained annually.

size from 1994 to 2002. Broadleaf height and stem diameter were similar across the control, 50 cm, and 100 cm treatments, regardless of whether the data set included tall aspen only, all aspen, or all aspen plus willow (Table 7). Moose browse of aspen was common on the Tyee Lake site, with the result that aspen height may not reflect the full growth potential of the species.

Neighbourhood broadleaf density was determined within a 1.78 m radius (10 m^2) of the crop pine. Aspen were removed from 0.785 m^2 and 3.142 m^2 areas within the 50 and 100 cm radius treatment subplots, respectively, but neither treatment significantly reduced density within the 10 m^2 subplot area in comparison with the untreated control. However, the overall average density of "all" aspen (i.e., averaged across the control, 50 cm, and 100 cm treatments) decreased from 44 stems per 10 m^2 subplot in 1994 to 19 stems in 2002 (densities are presented as "number of stems per subplot" rather than "number of stems per hectare" because subplots included both treated and untreated areas, and were therefore not representative of the entire treatment plot area). Neighbourhood tall aspen density decreased even more dramatically during the same period, from an average 23 stems in a 10 m^2 subplot to an average four stems per subplot. The decrease in tall aspen density is attributed to self-thinning, as well as to the rapid height growth of crop pine relative to small, low-vigour aspen stems.

Density per hectare of "all" aspen stems decreased in the untreated control from 50 200 to 21 900 stems ha^{-1} between 1994 and 2002, and decreases were approximately similar in the untreated portions of the 50 and 100 cm radius treatment subplots (Figure 4). Tall aspen density in the 50 and 100 cm treatments showed an apparent increase for 1 year following installation of the treatments, and then dropped to densities that were comparable to those in the control plots (Figure 5).

Tall aspen increased in height from an average of 49 to 331 cm between 1994 and 2002, which was slightly greater than the growth rate of the lodgepole pine seedlings (Figure 6). This trend is likely to continue and, therefore, aspen are expected to be taller than lodgepole pine for some time. A larger proportion of pine was rated as overtopped in 2002 than in 1999 (Figure 7), but this finding may be due to assessor subjectivity, since different contract-

TABLE 7 *Mean[a] aspen height, diameter, and density[b] in 50 and 100 cm radius brushing treatments[c] and the untreated control, 1994–2002*

		Tall aspen				All aspen				All aspen plus willow[d]			
		Control	50 cm	100 cm	p-value[e]	Control	50 cm	100 cm	p-value	Control	50 cm	100 cm	p-value
Height (cm)													
	1994	49 ± 2	51 ± 2	48 ± 2	0.7416	34 ± 3	35 ± 3	32 ± 3	0.7162	36 ± 2	37 ± 2	34 ± 2	0.6287
	1995	70 ± 2	68 ± 2	64 ± 2	0.2633	51 ± 2	50 ± 2	49 ± 2	0.8368	53 ± 2	52 ± 2	51 ± 2	0.3228
	1996	97 ± 4	93 ± 4	87 ± 4	0.3261	70 ± 4	68 ± 4	62 ± 4	0.3850	71 ± 3	68 ± 3	63 ± 3	0.2752
	1998	176 ± 10	165 ± 10	155 ± 10	0.2386	114 ± 7	106 ± 7	94 ± 7	0.2093	111 ± 7	102 ± 7	90 ± 7	0.1472
	2000	250 ± 18	238 ± 18	220 ± 18	0.2378	145 ± 12	134 ± 12	122 ± 12	0.3335	138 ± 11	124 ± 11	111 ± 11	0.2672
	2002	347 ± 26	345 ± 27	301 ± 26	0.1533	205 ± 17	191 ± 17	173 ± 17	0.4585	Data not collected			
Diameter (cm)													
	1994	0.6 ± 0.0	0.6 ± 0.0	0.6 ± 0.0	0.3898	0.4 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.9645	0.4 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.9305
	1995	0.9 ± 0.0a	0.8 ± 0.0b	0.8 ± 0.0b	**0.0032**	0.7 ± 0.0	0.6 ± 0.0	0.6 ± 0.0	0.3454	0.7 ± 0.0	0.6 ± 0.0	0.6 ± 0.0	0.2438
	1996	1.2 ± 0.1	1.0 ± 0.1	1.0 ± 0.1	0.0735	0.9 ± 0.1	0.8 ± 0.1	0.8 ± 0.1	0.2637	0.9 ± 0.0	0.8 ± 0.0	0.8 ± 0.0	0.2749
	1998	2.0 ± 0.2	2.0 ± 0.2	1.7 ± 0.2	0.3685	1.3 ± 0.1	1.3 ± 0.1	1.2 ± 0.1	0.6915	1.2 ± 0.1	1.1 ± 0.1	1.1 ± 0.1	0.6278
	2000	2.6 ± 0.2	2.2 ± 0.2	2.3 ± 0.2	0.2593	1.5 ± 0.1	1.4 ± 0.1	1.4 ± 0.1	0.5699	1.4 ± 0.1	1.2 ± 0.1	1.2 ± 0.1	0.6278
	2002	3.3 ± 0.2	3.1 ± 0.2	2.9 ± 0.2	0.3362	2.0 ± 0.1	1.8 ± 0.1	1.8 ± 0.1	0.4806	Data not collected			
Density per 10 m² subplot (r = 1.78 m)													
	1994	25 ± 4	26 ± 4	17 ± 4	0.1559	50 ± 9	48 ± 9	33 ± 9	0.2408	57 ± 10	55 ± 10	38 ± 10	0.2372
	1995	25 ± 5	28 ± 5	20 ± 5	0.4759	42 ± 9	46 ± 9	30 ± 9	0.4474	47 ± 9	51 ± 9	34 ± 9	0.4513
	1996	21 ± 4	23 ± 4	15 ± 4	0.4241	39 ± 7	40 ± 7	28 ± 7	0.4715	45 ± 7	45 ± 7	33 ± 7	0.4575
	1998	11 ± 2	12 ± 2	8 ± 2	0.5083	30 ± 5	29 ± 5	22 ± 5	0.4498	34 ± 5	34 ± 5	28 ± 5	0.6188
	2000	5 ± 2	6 ± 2	4 ± 2	0.7978	25 ± 4	24 ± 4	18 ± 4	0.3025	30 ± 5	30 ± 5	24 ± 5	0.5189
	2002	5 ± 1	4 ± 1	3 ± 1	0.7887	22 ± 2	19 ± 2	16 ± 2	0.0958	Data not collected			

a Values are presented in the form of "mean ± 1 standard error," where the standard error is based on the ANOVA model (i.e., variances are assumed to be homogeneous for all treatments and blocks).

b Density values are numbers of stems in 10 m² (r = 1.78 m) plots

c The site was cleared of aspen prior to the start of the study, and aspen removal in the 50 and 100 cm radius and broadcast treatments was maintained annually.

d A few scattered black cottonwood and birch stems were present on the site and were included in the analysis with willow.

e Values are in **bold** if they are significant at $p \leq 0.05$, according to analysis of variance. Means are assigned different letters if they are significantly different within the given year according to the Bonferroni test.

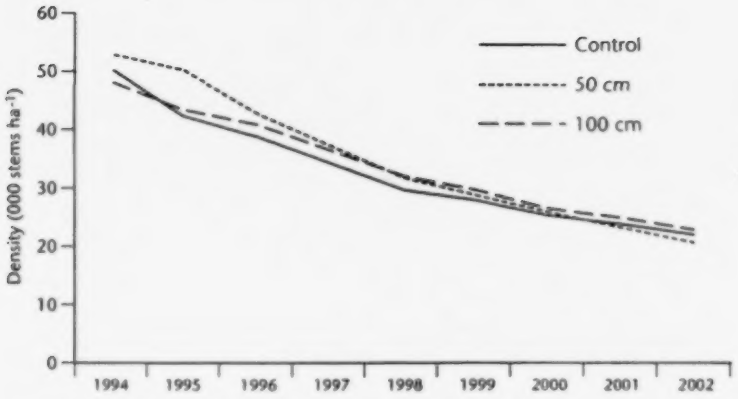

FIGURE 4 *Total aspen density (stems per hectare) in the untreated control, the 50 cm radius treatment, and the 100 cm radius treatment 1994–2002. Densities are based on the untreated area within the 10 m^2 subplots (10 m^2, 9.215 m^2, and 6.858 m^2 within the control, 50 cm, and 100 cm treatments, respectively). Interpolated values were used for 1997, 1999, and 2001 because no data were collected in those years.*

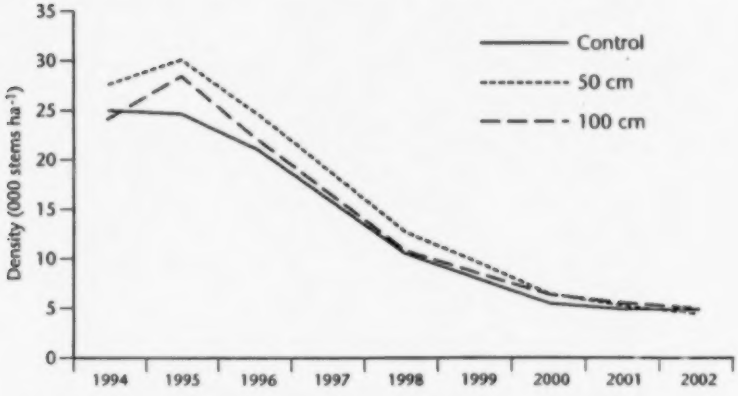

FIGURE 5 *Tall aspen density (stems per hectare) in the untreated control, the 50 cm radius treatment, and the 100 cm radius treatment 1994–2002. Densities are based on the untreated area within the 10 m^2 subplots (10m^2, 9.215 m^2, and 6.858 m^2 within the control, 50 cm, and 100 cm treatments, respectively). Interpolated values were used for 1997, 1999, and 2001 because no data were collected in those years.*

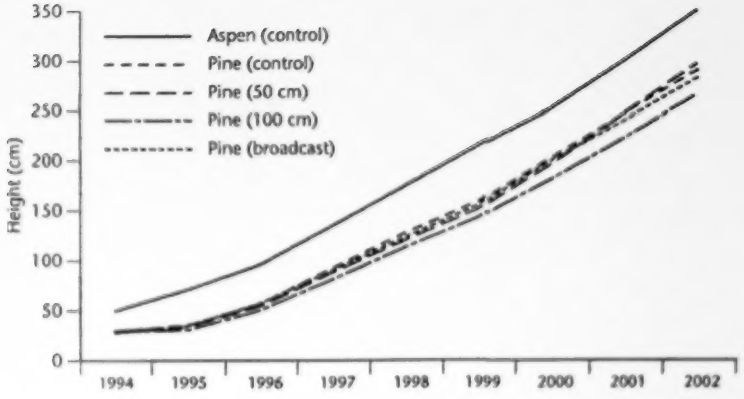

FIGURE 6 *Comparison of tall aspen and lodgepole pine height growth, 1994–2002. Tall aspen height is compared with pine height in the control, 50 cm radius, 100 cm radius, and broadcast treatments. Interpolated values were used for 1997, 1999, and 2001 because no data were collected in those years.*

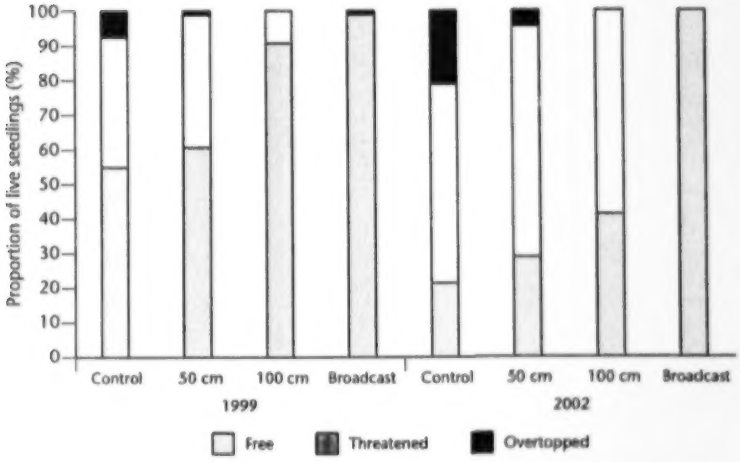

FIGURE 7 *Percentages of lodgepole pine seedlings that were free of vegetation, threatened by vegetation, or overtopped by vegetation in 1999 and 2002, in the control, 50 cm radius, 100 cm radius, and broadcast treatments.*

ors carried out measurements in those 2 years. Between 1999 and 2002, the proportion of pine seedlings that were "free" of competition decreased in the control and in the 50 and 100 cm radius treatments, while the proportion of "threatened" trees increased. The proportion of "overtopped" pine increased to 21% in the control and remained at 0% in the 100 cm radius and broadcast treatments. A small proportion of pine in the 50 cm radius treatment were overtopped because some individual aspen had grown tall enough to be out of reach during the annual maintenance of treatments.

4.2.2 Predicting lodgepole pine size from broadleaf abundance The calculation of Spearman's rank correlation coefficients showed that all lodgepole pine growth variables except HDR were negatively correlated with tall aspen density (based on density in the entire 10 m^2 subplot, not just the untreated portion of the plot) (Table 8). Pine stem diameter showed a somewhat stronger correlation than did height with tall aspen density. HDR showed a weak positive correlation with tall aspen density (i.e., HDR increased as tall aspen density increased).

Correlations between pine growth variables and all aspen density, or the density of all aspen plus willow, were inconsistently significant (Table 8), and the significant relationships were much weaker than the relationships with tall aspen. This implies that, up to 9 years after planting, tall aspen stems were more important competitors with the lodgepole pine than shorter aspen or willow stems. Including willow in the analysis did not improve the

TABLE 8 *Spearman's rank correlation coefficients for pairings between three categories of aspen density (tall aspen, all aspen, and all aspen plus willow) with lodgepole pine growth response variables*

Pine growth response variable		Tall aspen			All aspen			All aspen plus willow[a]		
		n	R[b]	p-value[c]	n	R	p-value	n	R	p-value
Stem diameter										
	2000	288	-0.6431	<0 0001	288	-0.0530	0.3705	288	-0.0959	0.1045
	2002	278	-0.5460	<0.0001	278	-0.1066	0.0759	data not collected		
Stem diameter increment	1994–2000	285	-0.6346	<0.0001	285	-0.0650	0.2739	285	-0.1048	0.0774
	1994–2002	275	-0.5396	<0.0001	275	-0.1166	0.0533	data not collected		
Height										
	2000	288	-0.5769	<0.0001	288	0.0735	0.2139	288	0.0304	0.6073
	2002	278	-0.4624	<0.0001	278	-0.0396	0.5106	data not collected		
Height increment										
	1994–2000	284	-0.5827	<0.0001	284	0.0629	0.2909	284	0.0158	0.7905
	1994–2002	274	-0.4699	<0.0001	274	-0.0392	0.5183	data not collected		
Leader length										
	2000	288	-0.4732	<0.0001	288	0.0419	0.4783	288	-0.0103	0.8620
	2002	263	-0.2285	0.0002	263	-0.1912	0.0018	data not collected		
Height:diameter ratio	2000	288	0.1149	0.0514	288	0.2240	0.0001	288	0.1947	0.0009
	2002	278	0.1940	0.0011	278	0.0837	0.1643	data not collected		

a A few scattered black cottonwood and birch stems were present on the site, and were included in the analysis with willow.
b R is the Spearman's rank correlation coefficient. A decrease in R from 0 to -1 or an increase from 0 to +1 implies a stronger correlation.
c p-values for Spearman's rank correlation coefficients ignore randomized block design (i.e., all points were considered independent).

correlation between lodgepole pine size and competing tree density, which suggests that willow were not contributing significantly to competition. For this reason, willow measurements were discontinued in 2002.

In 2002, correlations between pine growth variables and the basal area of tall aspen or all aspen were also tested (Table 9). Correlations between pine stem diameter and tall aspen basal area were moderate, but were weaker than the correlations between pine diameter and tall aspen density.

To further examine the relationship between tall aspen density and lodgepole pine growth, non-linear regression models were also fitted (Tables 10 and 11). Tall aspen density was generally a better predictor of pine size than tall aspen basal area. In 2002, when pine were 9 years old, tall aspen density explained 41% and 34% of the variation in pine diameter and height, respectively, whereas basal area predicted 18% of diameter variation and 8% of height variation. Scatterplots of stem diameter and height versus tall aspen density in 2002, with fitted regression lines, are shown in Figure 8.

4.2.3 Understorey vegetation During the 9-year measurement period, understorey vegetation (shrubs and herbs) showed a similar increase in cover across all four treatments (Table 12). In 1994, 1 year after the original aspen stand was cleared in preparation for this study, total vegetation cover averaged 21%. By 2002, it averaged 84%. Some of the difference between years may be due to assessor subjectivity, but the fact that the increases were approximately equal in the control and aspen removal treatments in all years suggests that the aspen removal treatments did not increase abundance of understorey vegetation. Average modal height of understorey vegetation increased from 26 cm in 1994 to 52 cm in 2002, and again the increases were approximately equal across all treatments. Broadleaf tree cover (within a 1.78 m radius around the crop pine) increased from 10 to 29% in the control, from 10 to 19% in the 50 cm treatment, and from 7 to 16% in the 100 cm treatment during the 9-year measurement period (Table 13).

TABLE 9 *Spearman's rank correlation coefficients for pairings between two categories of aspen basal area (tall aspen and all aspen) with lodgepole pine growth response variables, using 2002 data*

Pine growth response variable		Tall aspen basal area			All aspen basal area		
		n	R[a]	p-value[b]	n	R	p-value
Stem diameter	2002	278	-0.4204	<0.0001	278	-0.0973	0.1055
Diameter increment	1994–2002	275	-0.4171	<0.0001	275	-0.1099	0.0687
Height	2002	278	-0.2746	<0.0001	278	0.0792	0.1878
Height increment	1994–2002	274	-0.2829	<0.0001	274	0.0699	0.2488
Leader length	2002	263	-0.1154	0.0617	263	-0.0353	0.5691
Height:diameter ratio	2002	278	0.2600	<0.0001	278	0.2545	<0.0001
Crown length	2002	278	-0.3827	<0.0001	278	-0.0334	0.5797
Crown width	2002	278	-0.3827	<0.0001	278	-0.0581	0.3343

a R is the Spearman's rank correlation coefficient. Negative correlations improve as R decreases from 0 to -1; positive correlations improve as R increases from 0 to +1.

b p-values for Spearman's rank correlation coefficients ignore randomized block design (i.e., all points were considered independent).

TABLE 10 *Regression equation parameters[a,b] and R^2 values[c] for predicting lodgepole pine growth from tall aspen density*

Lodgepole pine growth response variable		n	a	b	c	R^2	RMSE	p-value
Stem diameter								
	2000	288	3.825	-0.040	n/a	0.512	0.641	<0.0001
	2002	278	5.497	-0.414	n/a	0.408	0.972	<0.0001
Stem diameter increment								
	1994–2000	285	3.491	-0.042	n/a	0.504	0.633	<0.0001
	1994–2002	275	5.167	-0.448	n/a	0.402	0.959	<0.0001
Height								
	2000	288	230.400	-0.035	n/a	0.481	39.432	<0.0001
	2002	278	326.100	-0.356	n/a	0.344	56.400	<0.0001
Height increment								
	1994–2000	284	216.800	-0.038	n/a	0.482	38.567	<0.0001
	1994–2002	274	311.900	-0.379	n/a	0.342	55.660	<0.0001
Leader length								
	2000	288	52.145	-0.034	n/a	0.301	12.342	<0.0001
	2002	263	53.980	-0.230	n/a	0.096	13.810	<0.0001
Height:diameter ratio	2000	288	60.294	0.113	-0.005	0.057	8.482	0.3550
	2002	278	58.960	8.440	-3.726	0.046	9.010	0.0012

a General form of non-linear regression model for all variables (except HDR) is: $y = ae^{bx} + \gamma_{block} + \delta_{treatment\ plot\ (block)} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density, and $\gamma_{block} + \delta_{treatment\ plot\ (block)}$ and ε are random errors associated with blocks, treatment plots within blocks, and the residual error.

b General form of regression model for HDR is: $y = a + bx + cx^2 + \gamma_{block} + \delta_{treatment\ plot\ (block)} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen density, and $\gamma_{block} + \delta_{treatment\ plot\ (block)}$ and ε are random errors associated with blocks, treatment plots within blocks, and the residual error.

c $R^2 = 1 - \sum (y - ae^{bx})^2 / \sum (y - \bar{y})^2$, where $\bar{y}$ is the overall mean.

TABLE 11 *Regression equation parameters[a] and R^2 values for predicting 2002 lodgepole pine growth from 2002 tall aspen basal area*

Lodgepole pine growth response variable		n	a	b	R^2	RMSE	p-value
Stem diameter		278	5.299	-0.043	0.181	1.143	<0.0001
Stem diameter increment	1994–2002	275	4.967	-0.047	0.183	1.121	<0.0001
Height		278	308.300	-0.031	0.080	66.780	<0.0001
Height increment	1994–2002	274	293.800	-0.033	0.081	65.800	<0.0001
Leader length		263	52.430	-0.020	0.022	14.370	0.1161
Height:diameter ratio		278	56.480	0.012	0.082	8.838	0.0052

a General form of non-linear equation for all variables is : $y = ae^{bx} + \gamma_{block} + \delta_{treatment\ plot\ (block)} + \varepsilon$, where y is one of the pine growth variables, x is tall aspen basal area, and $\gamma_{block} + \delta_{treatment\ plot\ (block)}$ and ε are random errors associated with blocks, treatment plots within blocks, and the residual error.

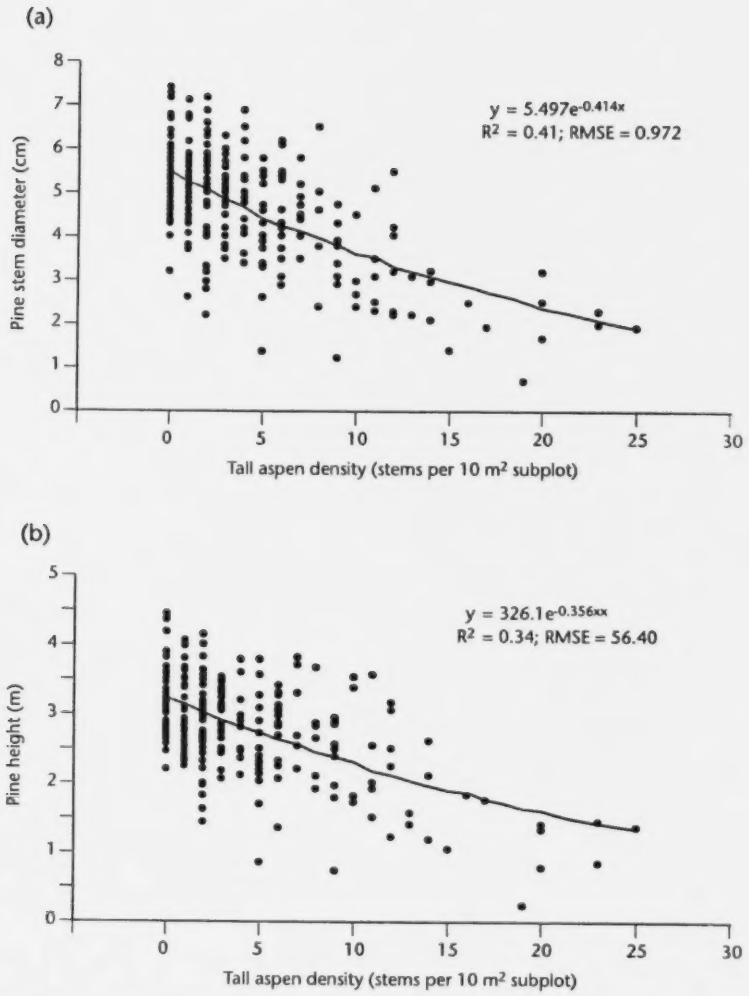
(a)
y = 5.497e-0.414x
R2 = 0.41; RMSE = 0.972
Pine stem diameter (cm)
Tall aspen density (stems per 10 m2 subplot)
(b)
y = 326.1e-0.356xx
R2 = 0.34; RMSE = 56.40
Pine height (m)
Tall aspen density (stems per 10 m2 subplot)

FIGURE 8 *Scatter plots and fitted non-linear regression equations describing the 2002 relationship between tall aspen density within the 10 m² subplot area (1.78 m radius around crop pine) and lodgepole pine size: (a) stem diameter, and (b) height.*

TABLE 12 *Mean cover[a,b] and modal height of understorey vegetation (shrubs and herbs) in 50 cm radius, 100 cm radius, and broadcast brushing treatments,[c] and the untreated control, 1994–2002*

		Control		50 cm		100 cm		Broadcast	
		Cover (%)	Modal height (cm)	Cover (%)	Modal height (cm)	Cover (%)	Modal height (cm)	Cover (%)	Modal height (cm)
Understorey vegetation	1994	22 ± 1	27 ± 1	19 ± 1	25 ± 1	21 ± 1	24 ± 1	22 ± 1	28 ± 1
	1995	23 ± 1	29 ± 1	23 ± 1	32 ± 1	21 ± 1	27 ± 1	-	-
	1996	37 ± 1	31 ± 1	38 ± 1	30 ± 1	38 ± 1	25 ± 1	37 ± 1	25 ± 1
	1998	38 ± 1	23 ± 1	37 ± 1	26 ± 1	37 ± 1	20 ± 0	38 ± 1	22 ± 1
	2000	63 ± 1	27 ± 1	57 ± 1	28 ± 1	51 ± 1	22 ± 1	52 ± 1	24 ± 1
	2002	85 ± 1	53 ± 3	86 ± 1	64 ± 2	86 ± 1	51 ± 2	80 ± 1	41 ± 1

a Values are presented in the form of "mean ± 1 standard error."
b Vegetation height and cover were assessed in a 1.78 m radius plot around the crop pine.
c The site was cleared of aspen prior to the start of the study, and aspen removal in the 50 and 100 cm radius and broadcast treatments was maintained annually.

TABLE 13 *Mean broadleaf tree cover[a,b] in 50 cm radius, 100 cm radius, and broadcast brushing treatments,[c] and the untreated control, 1994–2002*

	Cover (%)			
	Control	50 cm	100 cm	Broadcast
1994	10 ± 1	10 ± 1	7 ± 0	0 ± 0
1995	9 ± 1	6 ± 0	5 ± 0	0 ± 0
1996	9 ± 1	8 ± 1	5 ± 0	0 ± 0
2000	21 ± 1	16 ± 1	9 ± 1	0 ± 0
2002	29 ± 1	19 ± 1	16 ± 1	0 ± 0

a Values are presented in the form of "mean ± 1 standard error."
b Broadleaf cover was assessed in a 1.78 m radius plot around the crop pine.
c The site was cleared of aspen prior to the start of the study, and aspen removal in the 50 and 100 cm radius and broadcast treatments was maintained annually.

5 DISCUSSION

5.1 Lodgepole Pine Responses

Lodgepole pine survival at the Tyee Lake site was confounded by vole damage that occurred in 1994 and 1995. The heaviest damage was sustained in the control and the 50 cm radius treatments, probably because those treatments provided greater cover for the voles. By 2002, 13–28% of pine had died in the various treatments. Although vegetation competition may have been a contributing factor in some cases, none of the mortality was attributed solely to that cause because (1) aspen are not very competitive with pine in 4-year-old stands (Newsome et al. 2003), and (2) pine are known to survive for relatively long periods of time at low light (Wright et al. 2000). Some occurrences of defoliation and "spindly" stems (as a result of low light levels) were recorded in the 2002 assessment, but the majority of the surviving pine were in good or fair condition. Pine vigour will require ongoing assessment to determine the long-term effects of aspen competition. Other factors, such as western gall rust, are also affecting pine vigour at the Tyee Lake site. Finck et al. (1989)

report that this disease mainly attacks vigorously growing trees in open stands. Contrary to this finding, in our 9-year-old stands, the disease was more common in the control (20% occurrence) and 50 cm radius (26% occurrence) treatments than in the 100 cm radius and broadcast treatments (16–17% occurrence). Up to 25% of stems also displayed leader loss, forking, or distorted stem growth by age 9 years. The damaging agent has not been identified, but may be related to genetic characteristics of the seedlot.

As of 2002, none of the treatments had a significant effect on lodgepole pine stem diameter, stem diameter increment, height, or leader length compared with the untreated control. A trend of larger diameter in the broadcast treatment was developing but was not yet statistically significant ($p = 0.1237$), and not even the 2000–2002 pine diameter increment, which was considered to be one of the variables most likely to reflect the effects of aspen competition, showed a significant response to treatment. However, HDR was significantly higher in the control and 50 cm radius treatment than in the broadcast treatment, which suggests that trees in the denser neighbourhoods were beginning to lose diameter growth relative to height. Conifer stem diameter commonly responds more quickly than height to brushing-induced decreases in vegetation abundance (e.g., Lanner 1985; Lanini and Radosevich 1986; Simard et al. 2001). Results from the Cariboo-Chilcotin pine–aspen retrospective study, which took place in untreated stands, also showed that reductions in pine diameter as a result of increasing tall aspen density became significant at an earlier age than reductions in height (Newsome et al. 2003). At SBSdw1 sites that were included in the retrospective study, pine diameter showed a significant downward trend with increasing tall aspen density by age 7–12 years, whereas height trends were not consistent until age 17–18 years. Maintaining an aspen-free zone around young lodgepole pine may be less critical to their performance than controlling the density of tall aspen. If this is so, differences in pine growth between the 50 or 100 cm radius treatments and the untreated control at Tyee Lake may not be as profound as the differences in pine growth that were measured in the retrospective study as a result of increasing tall aspen density.

5.2 Neighbourhood Vegetation Responses

Broadleaf abundance was assessed in 1.78 m radius (10 m^2) plots around crop lodgepole pine. The broadcast treatment removed all broadleaf and willow stems, but neither the 50 nor 100 cm radius treatments significantly reduced the density (within the subplot area) of all aspen, tall aspen, or all broadleaves plus willow in comparison with the untreated control. Nonetheless, between 1994 and 2002, the density of "all aspen" decreased in individual treatments by more than 50% and density of "tall aspen" decreased by more than 80%. Both self-thinning and the fact that pine were growing faster than some of the less vigorous aspen stems likely contributed to the large decrease in tall aspen density.

Willow was abundant enough at the Tyee Lake site that it was thought possibly to be contributing to competition with lodgepole pine. However, Spearman's rank correlation analysis showed that the correlations between pine size and aspen abundance did not improve when willow stems were included along with the aspen, which suggests that they were not contributing substantially to competition. In contrast, Comeau et al. (2003) found that willow influenced light transmittance through the canopy in birch stands in northern British Columbia. In that study, the most successful models were

those in which coefficients were developed separately for birch and willow. However, willow is known for its plasticity (Brayshaw 1978), and is a more vigorous competitor in some ecosystems, and even on some sites, than others. At Tyee Lake, pine were taller than willow by the time the stand was 5 years old.

The brushing treatments applied at Tyee Lake were area-based and not selective, and, therefore, they did not affect the overall distribution of aspen diameters and heights among the remaining stems. For this reason, the treatments had no effect on aspen height or diameter relative to the untreated control.

5.3 Correlations between Aspen Abundance and Lodgepole Pine Size

Early results from the Cariboo-Chilcotin retrospective study (Newsome et al. 2003) showed that tall aspen density (i.e., the density of aspen as tall or taller than the crop pine) was the aspen abundance variable that was most strongly correlated with lodgepole pine growth. On the basis of that result, tall aspen density was used to test the correlation between aspen abundance and lodgepole pine growth in the present study at Tyee Lake. Spearman's rank correlation analysis was used to determine which lodgepole pine growth variables were most strongly correlated with tall aspen density. In this study, as in the retrospective study, lodgepole pine stem diameter and stem diameter increment showed stronger correlations with tall aspen density than did pine height, leader length, or HDR. This is consistent with the general understanding that height is independent of density unless density is extremely high (e.g., Daniel et al. 1979). Tall aspen density within a 1.78 m radius of the crop pine explained 41% of the variation in 9-year-old lodgepole pine stem diameter at Tyee Lake. Despite removal of aspen within 50 or 100 cm of the crop pine, the R^2 values are similar to those of the retrospective study for untreated stands, where tall aspen density explained 40–65% of the variation in stem diameter of 7- to 12-year-old pine at three different sites in the SBSdw1. When the Tyee Lake stand was 9 years old, pine diameter was less well correlated with tall aspen basal area than with tall aspen density, as was the case for 7- to 12-year-old pine in the retrospective study (Newsome et al. 2003). Nevertheless, the correlation between pine diameter and basal area may improve with age. In 10- to 30-year-old boreal aspen stands, Comeau (2002) found that aspen basal area was a good predictor of understorey light, which suggests that there should also be a good correlation between basal area and the stem diameter of shade-intolerant lodgepole pine.

5.4 Implications of Results with Regard to Free-growing Criteria

The primary objective of the study at Tyee Lake was to test the effectiveness of the free-growing requirement (current at the start of the experiment) that crop conifers be free of broadleaf competition within a 1 m radius (B.C. Ministry of Forests 1995). Criteria defining free-growing trees have been relaxed slightly since the time this study was established, so that overtopping broadleaves can now be present in one of four quadrants within a 1 m radius around crop conifers, as long as density limits are not exceeded (B.C. Ministry of Forests 2002). One of the original intentions of this study was to determine whether a broadleaf-free radius smaller than 1 m (i.e., 50 cm) would be adequate to ensure good growth of conifers. Such a change to the guidelines had the potential to reduce brushing costs or even to eliminate the need for brushing in some stands. The question of an appropriate broadleaf-free radius was particularly relevant for Cariboo-Chilcotin lodgepole pine–aspen stands, where healthy pine tends to be co-dominant with aspen. The two species increase in height at approximately the same rate, which

results in a relatively small height differential. In wetter climatic regions, aspen is likely to grow at a faster rate or carry more leaf area, and thus be a more vigorous competitor.

In 2002, when the pine–aspen stand at Tyee Lake was 9 years old, there were no significant differences in pine growth between any of the treatments, and neither was any mortality directly attributed to vegetation competition. Therefore, at the writing of this report, it is not yet possible to make recommendations with regard to adjusting the free-growing guidelines, which is one of the main objectives of the study. The significantly higher HDR in the untreated control and 50 cm treatment relative to the broadcast treatment may suggest that aspen competition is beginning to affect pine growth at Tyee Lake, but HDR is known to be a less reliable indicator of conifer vigour and ability to release from competition than other growth measures (Ruel et al. 2000). In addition, low HDR, which is associated with open-grown trees that are entirely free of competition, does not necessarily reflect the optimum growth strategy for sawlog timber production, where straight, tall trees with minimal branch size are preferred. Ideally, free-growing standards for lodgepole pine should aim to retain enough aspen competition for pine to optimize its height growth potential, to minimize branch size, and to reduce the percent crown, without causing significant decreases in diameter growth or mechanical stability.

British Columbia's free-growing guidelines are intended to ensure that conifers are free of competition that will compromise their development over the course of a rotation; therefore, the current requirement for trees of free-growing age to be free of overtopping vegetation within a 1 m radius sets the standard for conifer performance. In this study, the 1 m spatial requirement is represented by the 100 cm radius treatment. If long-term pine performance in the 50 cm radius treatment is at least as good as that of pine in the 100 cm radius treatment, then changes to the free-growing guidelines may be warranted. After 9 years, none of the treatments applied at Tyee Lake was associated with statistically significant reductions in pine growth. Moose browse at the study site reduced aspen growth and performance, which may have delayed or reduced the competitive effects experienced by lodgepole pine; however, moose browse is extremely common in the SBSdw subzone and its effect at Tyee Lake is likely within the range of normal occurrences.

Although the primary focus of this project is related to the spatial arrangement of aspen (i.e., determining the minimum distance around pine that must be aspen-free), the results may eventually help determine whether controlling aspen density on a broadcast basis is more important to pine performance than controlling the spatial arrangement of aspen in relation to pine. Compared with SBSdw1 sites studied in the Cariboo-Chilcotin pine–aspen retrospective study (Newsome et al. 2003), tall aspen densities at Tyee Lake were, on average, relatively low in all treatments, including the untreated control (average of five, four, and three tall aspen per 1.78 m plot in the control, 50 cm radius, and 100 cm radius treatments, respectively). Nonetheless, aspen densities in the 50 and 100 cm treatments and the control exceeded the current allowable limit (B.C. Ministry of Forests 2002) and were variable across the site, with as many as 25 tall aspen per 1.78 m plot occurring in some blocks. Photographs of the 50 cm radius and broadcast treatments are shown in Figure 9.

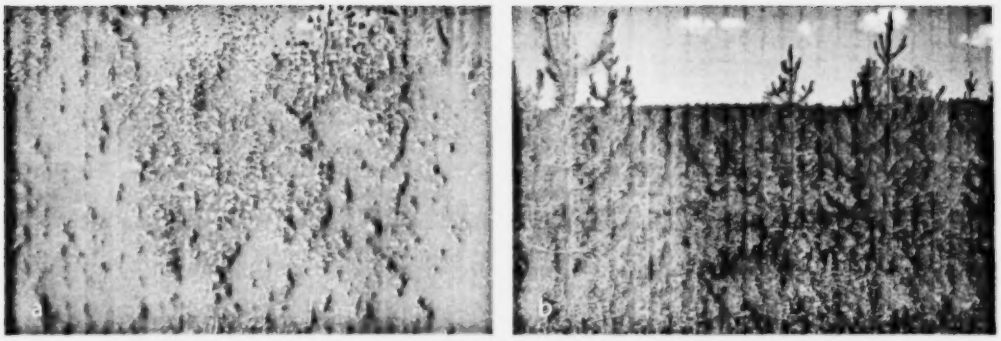

FIGURE 9 *Nine-year-old lodgepole pine and surrounding vegetation in a) the 50 cm radius treatment and b) the broadcast removal treatment.*

Lodgepole pine growing in the broadcast and 100 cm treatments are now, by definition, free-growing because they are free of overtopping vegetation within a 1 m radius and they exceed the minimum requirements for age and height. However, differences in pine performance as a result of the treatments are not yet well-defined, and we cannot yet say whether the current guidelines are biologically appropriate for pine–aspen stands in the SBSdw2. Eventually, the treatments applied in this study will produce a range in pine performance that can be used to determine whether or not the current standards are appropriate for producing the desired outcome.

5.5 Future Work

The Tyee Lake study requires further assessment because the effects of competition between aspen and lodgepole pine have not yet been fully expressed. As shown by the Cariboo-Chilcotin pine–aspen retrospective study (Newsome et al. 2003), the effects of aspen competition on pine in the SBSdw subzone increase at least up to stand age 15–19 years. With regard to the primary objective of the study, which was to investigate the appropriateness of the 1 m radius spatial criterion used to define free-growing, it is not yet possible to draw a conclusion because none of the treatments, including the untreated control, has resulted in a decline in survival or vigour of lodgepole pine. Further assessments will also provide information about the most appropriate age to treat pine–aspen stands in this subzone. According to B.C. Ministry of Forests guidelines, pine must be free-growing by age 15, at the latest. Pine at Tyee Lake will be 15 years old in 2008, at which time free-growing assessments will be done. At that point, removal of aspen will cease and pine response will be followed to determine its performance across the treatments. These data will assist in evaluating the spatial components of the free-growing guidelines after free-growing is declared. Finally, much more in-depth analysis is planned regarding the spatial aspects of competition between pine and aspen. Throughout the study, data have been collected regarding the distance of aspen from crop pine within the 1.78 m radius subplots. These data require further analysis, and have the potential to be used in developing a spatial model for the competitive relationship between aspen and pine.

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Code	Overall Seedling Condition
1 Good	Seedling shows no signs of stress, has a vigorous growth rate and a generally healthy appearance.
2 Fair	Seedling is under some form of stress, may have minor defects and has a moderate growth rate.
3 Poor	Seedling is under severe stress, may have major defects, and has a poor growth rate.
4 Moribund	Seedling is almost dead.
5 Dead	
6 Missing	
7 Destructively sampled	

	Seedling Vegetation Cover Codes
O Overtopped	The leader of the crop tree is at present overtopped by surrounding vegetation; crop tree available sunlight is greatly reduced.
T Threatened	The leader of the crop tree is at or near the same height of the surrounding vegetation, and/or is likely to be overtopped within two growing seasons.
F Free Growing	The leader of the crop tree is well above the surrounding vegetation and is not likely to become threatened.

Seedling Damage Codes

Stem Condition Code

H – No visible effect (healthy)
P – Bark peeled or abraded
B – Stem bent
S – Stem smashed, crushed, trampled
C – Stem cut, clipped, broken
D – Tree dead, dying
M – Tree missing
F – Stem forked
G – Gall rust
Ø – Other symptoms (specify)

Foliage Condition Code

H – No visible effect (healthy)
Y – Chlorotic (yellow)
M – Mottled
N – Necrotic
A – Needles absent, defoliated
B – Browsed
D – Dead buds on lateral branches
G – Gall aphid
Ø – Other symptoms (specify)

Damage Cause Code

A – None
H – Herbicide
M – Mechanical equipment
T – Hand tools
S – Falling slash (human caused)
X – Falling or sliding debris
E – Climate – frost
N – Snow press
V – Vegetation press
W – Climate – drought
R – Rodents, small animals
B – Big game

Leader Shoot Condition Code

H – No visible effect (healthy)
C – Curled
F – Forked
B – Browsed
T – Dead terminal bud
S – Snapped, broken
A – Absent, missing
P – Pissodes
Ø – Other symptoms (specify)
N – No or abnormal flush

L – Livestock
F – Fire
I – Insects
D – Disease
Z – Destructively sampled
G – Winter damage
P – Whipping damage
Ø – Other (specify)
U – Unknown